Pacific Science (1998), vol. 52, no. 2: 141–150

Benthic Communities Associated with Carbonate Rubble and Adjacent Soft Sediments in a Shallow Coastal Area of O'ahu, Hawai'i[1]

S. A. McCarthy,[2] J. H. Bailey-Brock,[3] and W. A. Estabrooks[3]

ABSTRACT: Although the shallow, wave-swept sedimentary environment of the near-shore subtidal region of Hawai'i would be expected to be characterized by a relatively homogenous community associated with shifting sediments, small-scale variability in the macrofauna exists. Benthic communities associated with rubble are distinct from nearby sand areas. Higher densities, taxonomic richness, and benthic biomass are characteristic of sediments containing carbonate rubble fragments (ranging from 2 to 64 mm in size). Rubble communities are dominated by annelids and a variety of crustaceans (primarily amphipods, isopods, and tanaids); sand communities are dominated by nematodes. The unconsolidated carbonate rubble community displays an undisturbed Abundance Biomass Comparison (ABC) pattern; the sand community displays a disturbed pattern. The divergent ABC patterns may reflect differences in substrate stability.

Small-scale spatial variations in soft-bottom benthic communities are well documented and have been related to small-scale disturbances (e.g., Thistle 1981, Van Blaricom 1982), sedimentary microtopography (e.g., Hogue and Miller 1981, Sun and Fleeger 1994), and the presence of secondary structures (e.g., polychaete tubes, seagrass blades) within sediments (e.g., Woodin 1978, Bailey-Brock 1979, Gallagher et al. 1983). Secondary structures within sediments tend to have a diversifying effect on a community (Sebens 1991). Carbonate rubble, resulting from the fragmentation of coral reefs, is an example of a secondary structure commonly present in sediments of Hawai'i and other coastal areas of the Tropics. Coral rubble can provide bioeroder species a refuge from predation and a suitable site for particulate feeders to lodge. The rubble is an in situ substrate for organisms to attach to or bore into; empty burrows of previous residents may form refuges for motile cryptic species. In addition, study of energy turnover in sand, rubble, and coral areas of a Philippine reef system demonstrated sand areas to be net heterotrophic ($P/R < 1$), with increased production in rubble areas ($P/R = 1$) (Yap et al. 1994). This suggests that the benthic communities associated with sediments containing carbonate rubble are distinct.

In this study we examined the benthic communities associated with sediments containing carbonate rubble and those without rubble in a shallow water (10 m depth) area off the south shore of O'ahu, Hawai'i. We also examined whether benthic communities associated with carbonate rubble, with its increased structural complexity, stability within the sediment, ability to serve as a refuge from predation and higher P/R ratio, support a relatively undisturbed community with higher density, biomass, and diversity than adjacent sediments lacking rubble.

[1] This study was funded in part by a grant from the Bishop Museum Edmondson Research Fund to S.A.M. Manuscript accepted 23 July 1997.
[2] Department of Oceanography, School of Ocean and Earth Science and Technology, University of Hawai'i, 1000 Pope Road, Honolulu, Hawai'i 96822. Author to whom correspondence should be addressed. Current address: 8944 Miller Lane, Vienna, Virginia 22182.
[3] Department of Zoology, University of Hawai'i at Mānoa, Honolulu, Hawai'i 96822.

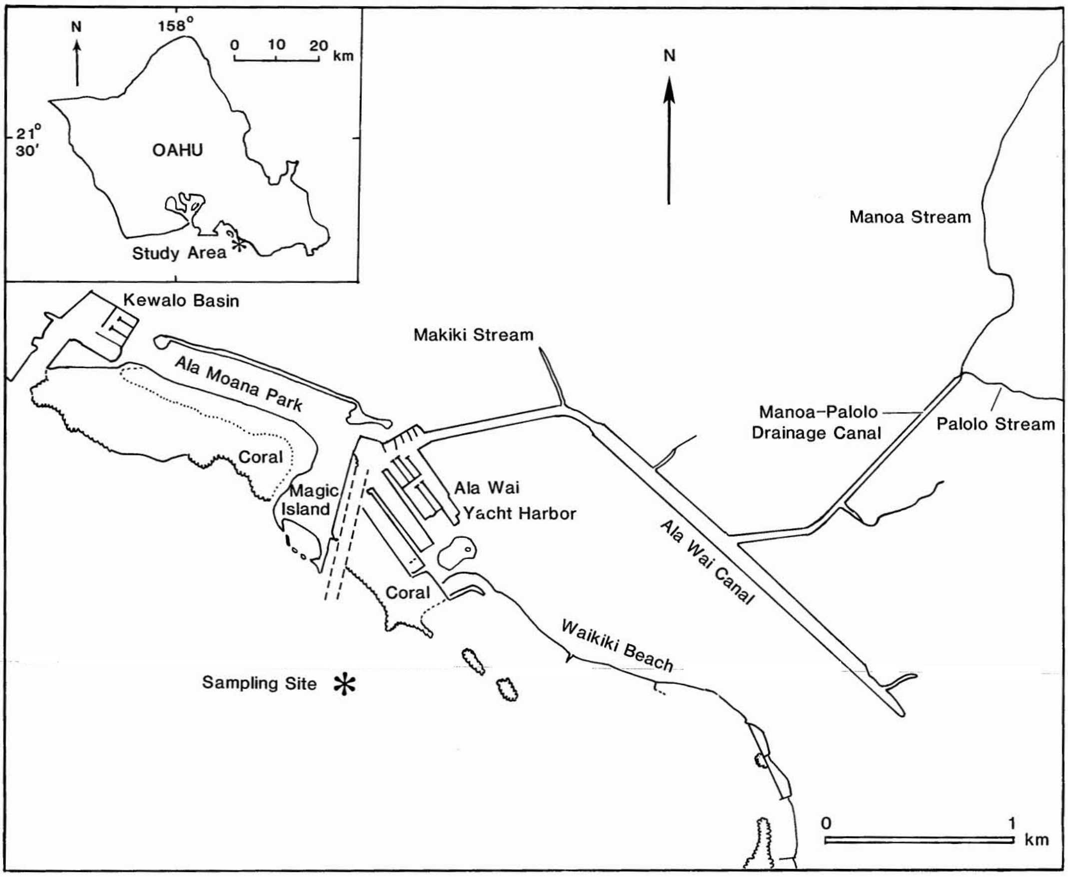

FIGURE 1. Location of study area off the south shore of O'ahu, Hawaiian Islands. Samples were collected adjacent to a sand channel (parallel dashed lines) leading out of the Ala Wai Yacht Harbor.

MATERIALS AND METHODS

Study Site and Sample Processing

Benthic communities within the sediments of a shallow (10 m depth) soft-bottom coastal site off O'ahu, Hawai'i, were examined (Figure 1). The area is located near the mouth of the Ala Wai Canal, a highly modified drainage canal, which has been described as one of the most heavily fertilized estuaries in the world (Laws et al. 1994). Replicate samples were taken from within a sand channel (approximately 25 m wide) oriented north to south (inshore to offshore), bordered to the west and east by relatively low-relief coral reef (1–1.5 m high).

For macrofaunal analysis, quantitative samples of the sediment were obtained using a hand-held corer (10.5 cm diameter) inserted approximately 10 cm into the sediment by divers using scuba. The core depth of some samples containing large rubble fragments was less than 10 cm. Sediment within the sand channel studied showed an obvious gradation from "sand only" to a "sand and rubble mixture." Rubble is defined as calcium carbonate fragments whose particle diameter ranges in size from 2 to 64 mm. These fragments were generally fragmented pieces of coral. The macrobenthic community composition, density, and biomass of the samples composed primarily of sand (less than 10 cm^3

rubble per 86.5-cm^2 area sampled) were compared with the same parameters of an adjacent area containing both sand and rubble. In this study "rubble" samples were defined as those sediments containing greater than 40 cm^3 rubble per 86.5-cm^2 area sampled. Samples were obtained in August 1993, November 1993, and February 1994. Comparison of the relative disturbance level of the two sedimentary types was made using Abundance Biomass Comparisons (Warwick 1986) on the community present in each. Rubble samples were compared with sand samples using *t*-tests on log-transformed data. All biological data were tested for normality (Shapiro-Wilk equivalent) and homogeneity of variances (*F*-max test) before application of statistical tests.

Samples were fixed in 10% seawater-buffered formalin with rose bengal for a minimum of 48 hr. After fixation, samples with rubble fragments were sieved through a 2-mm-mesh sieve to separate the rubble from the sand. The remaining sand sample was sieved through a 0.5-mm-mesh sieve. The sediment and macrofauna retained on the sieve were stored in 70% alcohol and used for determination of community structure and biomass (ash-free dry weight). For samples with rubble, volume displacement was used to determine the amount of rubble present. An acid dissolution technique was employed to recover the endolithic, cryptic, and sessile epifaunal organisms present within the coral rubble (Brock and Brock 1977). Upon dissolution of the carbonate rubble, the samples were passed through a 0.5-mm-mesh sieve, and the organisms retained were transferred to 70% alcohol.

Macrofauna biomass (ash-free dry weight [AFDW]) was determined for representative samples from each sedimentary type. Samples were sorted by separating infauna from sedimentary material and organisms identified. Structural parts of organisms were mechanically removed from mollusks (shells) and polychaetes (tubes). After the structures were removed from the organisms, the samples were dried to a constant weight (100°C), and the AFDW determined (4 hr at 550°C). Individuals belonging to the same taxon from all replicates were pooled to produce one biomass value per taxon. An average weight for an individual of each taxon was determined and used to back-calculate the taxon weight per replicate.

Community comparisons were made using major taxonomic groups: mollusk, echinoderm, annelid, crustacean, nematode, and other taxa. The group "other taxa" includes cephalochordates, nemerteans, platyhelminths, sipunculans, and cnidarians. Species-level data for many of the taxa in this study are available in McCarthy (1996). Taxonomic richness was examined by summing the species (or lowest taxonomic group identified). Macrofauna diversity was evaluated using *k*-dominance curves (Lambshead et al. 1983). The Abundance Biomass Comparison (ABC) method proposed by Warwick (1986) was employed to help characterize the disturbance status of the community. It has been proposed that this technique is sensitive to both natural physical and biological perturbations as well as pollution-induced disturbance (Warwick et al. 1987).

To characterize the relative stability of the sediments, the percentage frequency of near-bed wave-induced oscillatory velocities was calculated. Equation 1 (Denny 1988) was used in conjunction with the annual summary of significant wave heights and corresponding peak periods for O'ahu's south shore (Army Corps of Engineers 1994) to determine the near-bed wave-induced velocities experienced for the period February 1993–December 1993.

$$U_0 = \frac{(\pi H)}{\tau} \Big/ \sin h \, \frac{2\pi d}{L} \tag{1}$$

(U_0, "near-bed" velocity; H, wave height; d, water depth; τ, peak period; L, wavelength.) Shallow-water wavelength was calculated as presented in equation 2 (Denny 1988).

$$L = \tau (gd)^{0.5} \tag{2}$$

A graphic representation of the frequency of occurrence of a range of wave-induced near-bed velocities at 10 m depth along O'ahu's south shore was constructed.

TABLE 1

COMPARISON OF COMMUNITY PARAMETERS BETWEEN "SAND" AND "RUBBLE" FROM A SHALLOW COASTAL AREA OFF O'AHU, HAWAI'I

COMMUNITY PARAMETER	SAND (MEAN $\pm$ 1 SD)	RUBBLE (MEAN $\pm$ 1 SD)	STATISTICAL RESULTS
Total macrofauna density (no. of individuals/m^2)	8,686 $\pm$ 5,818 ($n = 7$)	22,744 $\pm$ 13,612 ($n = 8$)	t-test *($P = 0.028$)
Annelid density (no. of individuals/m^2)	1,823 $\pm$ 949 ($n = 7$)	9,124 $\pm$ 6,136 ($n = 8$)	Mann-Whitney *($P = 0.009$)
Crustacean density (no. of individuals/m^2)	1,363 $\pm$ 772 ($n = 7$)	6,423 $\pm$ 5,197 ($n = 8$)	t-test *($P = 0.028$)
Nematode density (no. of individuals/m^2)	3,777 $\pm$ 3,475 ($n = 7$)	2,931 $\pm$ 1,280 ($n = 8$)	t-test N.S. ($P = 0.72$)
Other taxa density (no. of individuals/m^2)	1,724 $\pm$ 1,275 ($n = 7$)	3,132 $\pm$ 2,089 ($n = 8$)	t-test N.S. ($P = 0.17$)
Echinoderm density (no. of individuals/m^2)	0 ($n = 7$)	143 $\pm$ 147 ($n = 8$)	N/A
Mollusk density (no. of individuals/m^2)	0 ($n = 7$)	991 $\pm$ 1,116 ($n = 8$)	N/A
Taxonomic richness (no. of taxa)	11 $\pm$ 2 ($n = 7$)	27 $\pm$ 9 ($n = 8$)	t-test *($P < 0.001$)
Total macrofauna biomass (mg/m^2)	76 $\pm$ 67 ($n = 5$)	2,918 $\pm$ 1,928 ($n = 4$)	t-test *($P = 0.006$)

NOTE: Statistical tests and results are provided for comparisons between "sand" and "rubble" (*, significant at $\alpha = 0.05$; N.S., not significant; n, number of samples).

For sediment grain size analysis of the "sand" area, quantitative samples of the sediment were obtained using a hand-held corer (2.1 cm) inserted 8 cm into the sediment by divers using scuba. Samples were initially processed wet to separate the sand from the mud fraction. The sand was then dry sieved (Buchanan 1984).

RESULTS

Benthic Community Overview

Table 1 compares the mean total macrofauna density, taxonomic richness, and faunal biomass of "sand" samples and those of "rubble." A significant difference exists in total macrofauna biomass, taxonomic richness, and density of annelids, crustaceans, and total macrofauna between these communities. "Rubble" samples have significantly higher densities of annelids and crustaceans, with total macrofauna densities approximately 2.6 times higher when compared with sand samples. Densities of annelids and crustaceans are 5 and 4.7 times higher, respectively, in "rubble" than in adjacent sand. Taxonomic richness and total macrofaunal biomass were also higher in "rubble" samples. Taxonomic richness is 2.5 times higher in "rubble" samples than in sand (Tables 1 and 2). Mean total macrofauna biomass is 38.3 times higher in "rubble" samples than in sand. Figure 2 compares the community composition of "sand" and "rubble." The rubble community is dominated numerically by annelids (polychaetes and oligochaetes) and crustaceans. The sand community is dominated numerically by nematodes. Echinoderms and mollusks are only present in rubble samples. The k-dominance curve of the rubble community is less than the curve for sand communities for all values of k (Figure 3). This result is indicative of a more diverse community associated with sediments containing a large rubble fraction.

Evaluation of Community Disturbance

The ABC of the "rubble" community was distinct from the ABC curves associated with

TABLE 2

Comparison of Community Composition between "Sand" and "Rubble" from a Shallow Coastal Area Off O'ahu, Hawai'i

TAXONOMIC GROUP	SAND	SAND AND RUBBLE
Chordata		
Cephalochordata		*
Hemichordata		*
Chaetognatha		*
Mollusca		
Gastropoda		
Prosobranchia		*
Opisthobranchia		*
Bivalvia		*
Echinodermata		
Ophiuroidea		*
Echinoidea		
Echinacea		*
Annelida		
Oligochaeta	*	*
Polychaeta		
Amphinomidae		*
Capitellidae	*	*
Chaetopteridae		*
Cirratulidae		*
Dorvilleidae		*
Eunicidae		*
Glyceridae		*
Hesionidae	*	*
Magelonidae	*	*
Nereididae		*
Opheliidae		*
Palmyridae		*
Phyllodocidae		*
Pilargidae	*	*
Pisionidae	*	*
Poecilochaetidae	*	*
Polynoidae		*
Protodrilidae	*	*
Questidae	*	*
Sabellidae	*	*
Serpulidae	*	*
Sigalionidae		*
Spionidae	*	*
Syllidae	*	*
Terebellidae		*
Arthropoda		
Arachnida	*	*
Pycnogonida		*
Copepoda	*	*
Ostracoda	*	*
Malacostraca		
Decapoda		
Anomura		*
Brachyura		*
Caridian		*
Amphipoda	*	*
Tanaidacea	*	*
Isopoda	*	*
Cumacea		*
Stomatopoda		*
Nemertea	*	*
Nematoda	*	*
Sipuncula	*	*
Platyhelminthes	*	*
Bryozoa	*	*
Phoronida	*	
Cnidaria		*

*, Present; $n = 7$ for "sand"; $n = 8$ for "rubble."

"sand" communities (Figure 4). The "sand" community had ABC curves indicative of a disturbed system, with the numerical abundance curve above the biomass curve for all values of k (species rank). The ABC curves of the "rubble" community were indicative of an undisturbed system, with the biomass curve exceeding the numerical abundance curve for all values of k.

Wave-Induced Near-Bed Oscillatory Velocities and Sediment Grain Size Analysis

Wave-induced oscillatory velocities calculated for O'ahu's south shore indicate that velocities in excess of 25 cm/sec occur with a frequency greater than 85%. The maximum velocity calculated was 70 cm/sec (Figure 5). Greater than 90% of the "sand" was composed of particles with a diameter less than 0.5 mm (Figure 6).

DISCUSSION

In this study, sediments containing carbonate rubble supported a more diverse benthic community with higher densities and biomass than nearby sand areas (Table 1 and Figure 3). This is not surprising because, relative to sand, carbonate rubble has higher structural complexity, increased sediment stability, may serve as a refuge from predation, and has been shown to have a higher P/R ratio (Yap et al. 1994). The higher taxonomic richness of the rubble is due in part to the greater variety of crustaceans and epifauna associated with

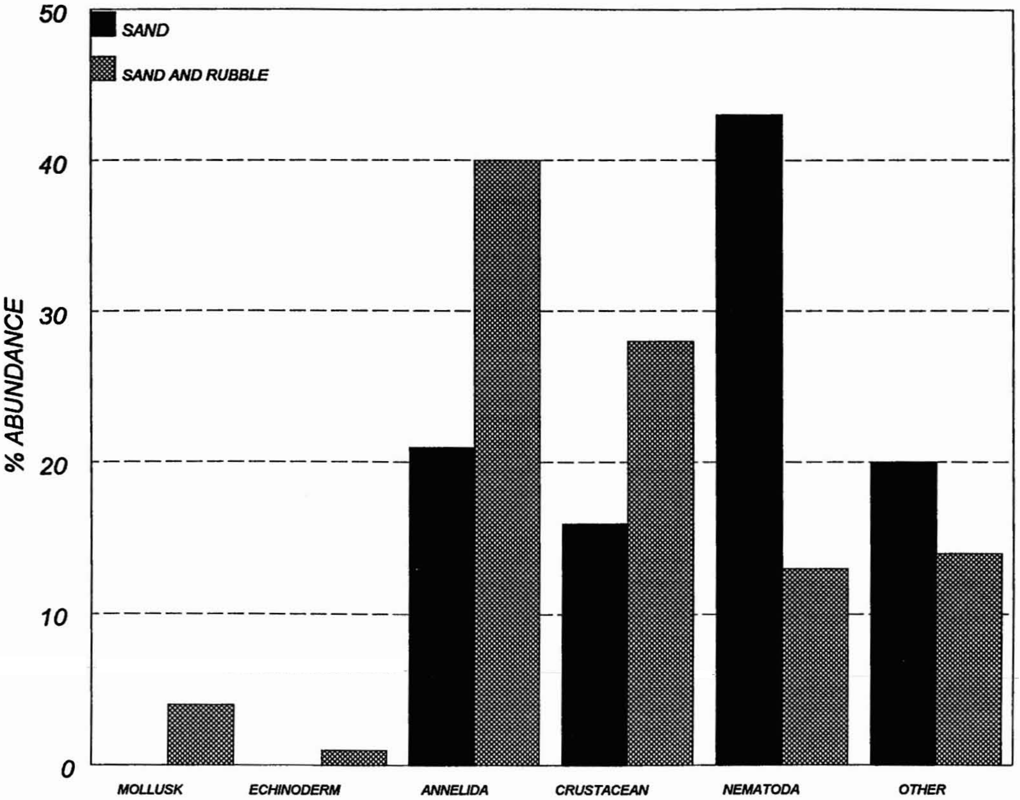

FIGURE 2. Comparison of the community composition (expressed as percentage abundance) between "sand" and "rubble" communities ($n = 7$ for "sand" and $n = 8$ for "rubble").

the rubble fraction (Table 2). Environments with dead coral rubble and gravel components are known to harbor distinct communities (Jones 1984) with diverse amphipod (Myers 1985) and epifaunal assemblages (Hartnoll 1983).

The higher densities and biomass in sediments containing rubble are consistent with the findings of Brock and Smith (1983) in Kāne'ohe Bay, Hawai'i, where endolithic communities associated with coral substrata had significantly higher biomass than nearby soft sediment communities. Values for standardized community biomass (mg DW ml^{-1}) of the carbonate rubble communities of this study (31 ± 14 mg DW ml^{-1}) are comparable with those obtained by Brock and Smith (1983) for the Kāne'ohe Bay reef slope region (post sewage outfall diversion), where the values ranged from 18 ± 9 mg DW ml^{-1} to 39 ± 33 mg DW ml^{-1}. The biomass results from this study are considerably less than the 220 ± 118 mg DW ml^{-1} reported in Brock and Smith (1983) from hard substrate samples taken from the reef slope area during the time period of elevated particulate loading from sewage effluent. The relatively low density of suspension-feeding polychaetes in the rubble fraction of the study reported here and the polychaete biomass dominance of detritivores (primarily members of the Glyceridae, Capitellidae, Nereidae, and Syllidae) indicates that particulate loading within the water column at this site is relatively low and unpredictable. This suggests that the Ala Wai Canal had little influence on the benthos.

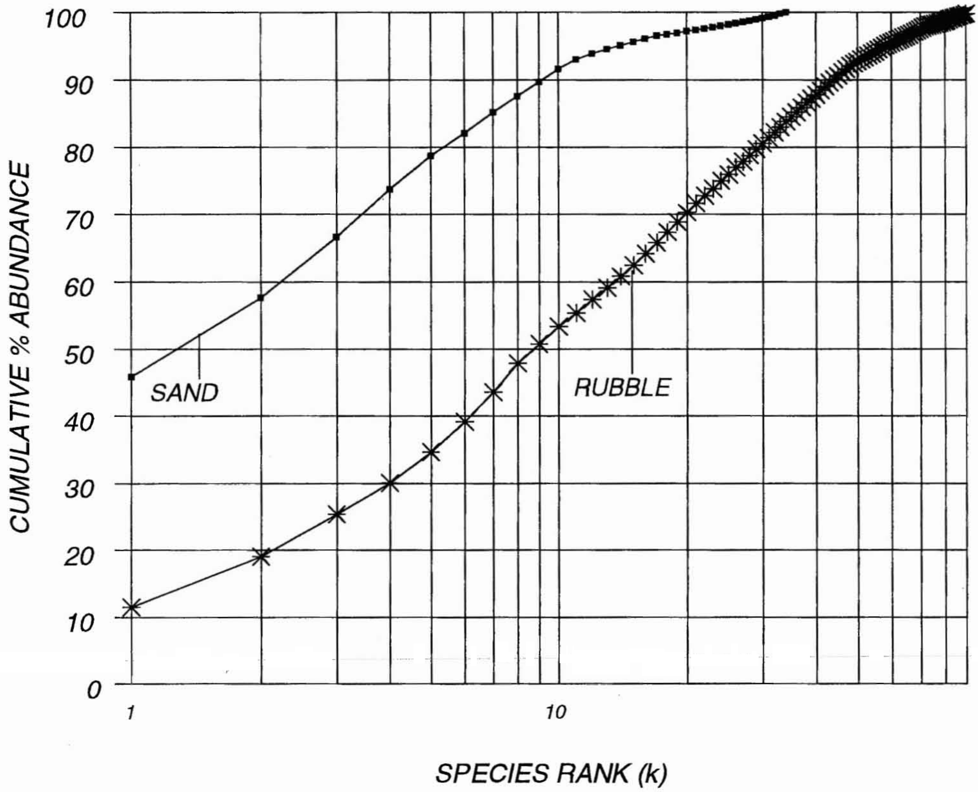

Figure 3. *k*-dominance curves for "sand" and "rubble" communities.

The ABC technique has been used to identify both natural and anthropogenic disturbance in benthic communities (Warwick 1986, Warwick et al. 1987). In the study reported here, the ABC technique characterized the communities associated with rubble as distinct and undisturbed, as defined by Warwick (1986); the sand communities were classified as disturbed. Because both the rubble and sand communities are in close proximity, it is unlikely that the results from the disturbed sediments are a reflection of anthropogenic influences, but may be a reflection of the relative instability of the sand compared with that of the rubble. Current velocities in excess of 25 cm/sec are capable of moving sediment grains in the 0.125- to 0.250-mm size class, and those in excess of 80 cm/sec are capable of moving sediment grains in the "rubble" (2 to 64 mm) size class (Hiscock 1983). Although these values were originally determined for quartz sediments, they provide a baseline for examining the carbonate sediments of this area. The maximum wave-induced near-bed oscillatory velocity calculated in this study was below 80 cm/sec, the critical erosion velocity for "rubble," suggesting that the rubble substrate was relatively stable (Figure 5). In contrast, for "sand," near-bed velocities in excess of 25 cm/sec occurred with a frequency exceeding 85%. Over 50% of the "sand" was composed of sediment grains in the size class transported by velocities in excess of 25 cm/sec, suggesting that "sand" was a very unstable substrate, frequently in motion (Figures 5 and 6). The differential stability of sand and adjacent rubble could produce two distinct communities, one reflecting the disturbance associated with a constantly shifting substrate (sand) and the other being a reflection of the undisturbed condition asso-

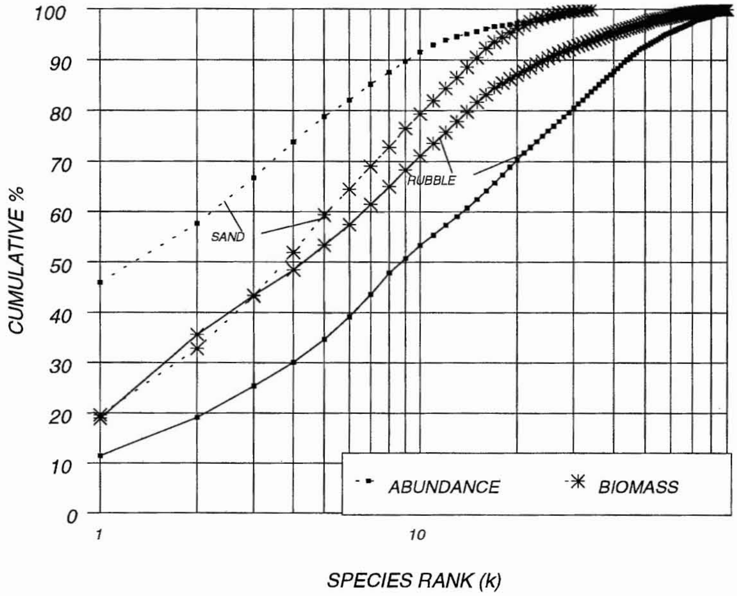

FIGURE 4. Abundance Biomass Comparison (ABC) curves for "sand" and "rubble" communities (dashed lines represent "sand" community, solid lines represent "rubble" community).

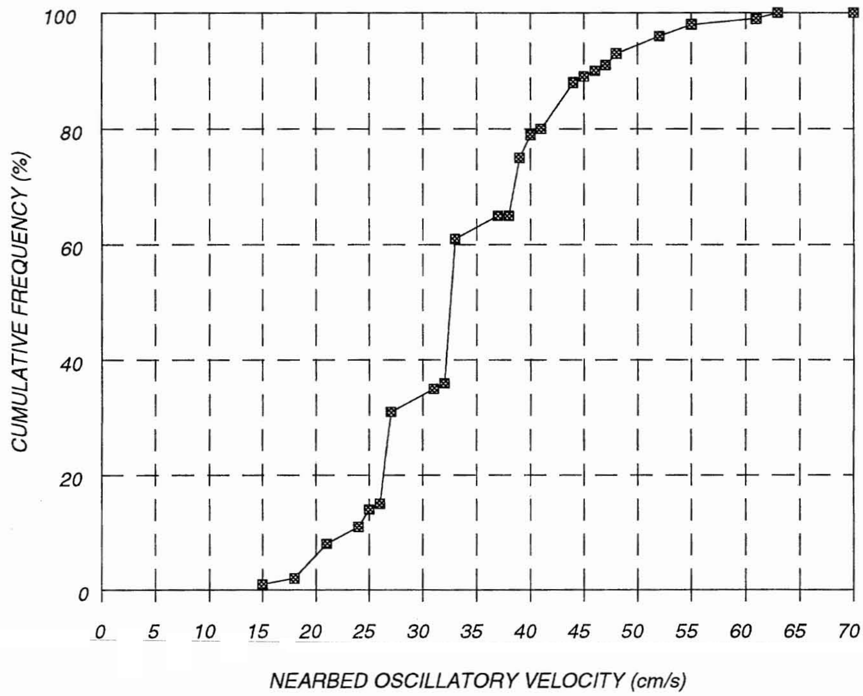

FIGURE 5. Cumulative percentage frequency of near-bed wave-induced velocities (February–December 1993).

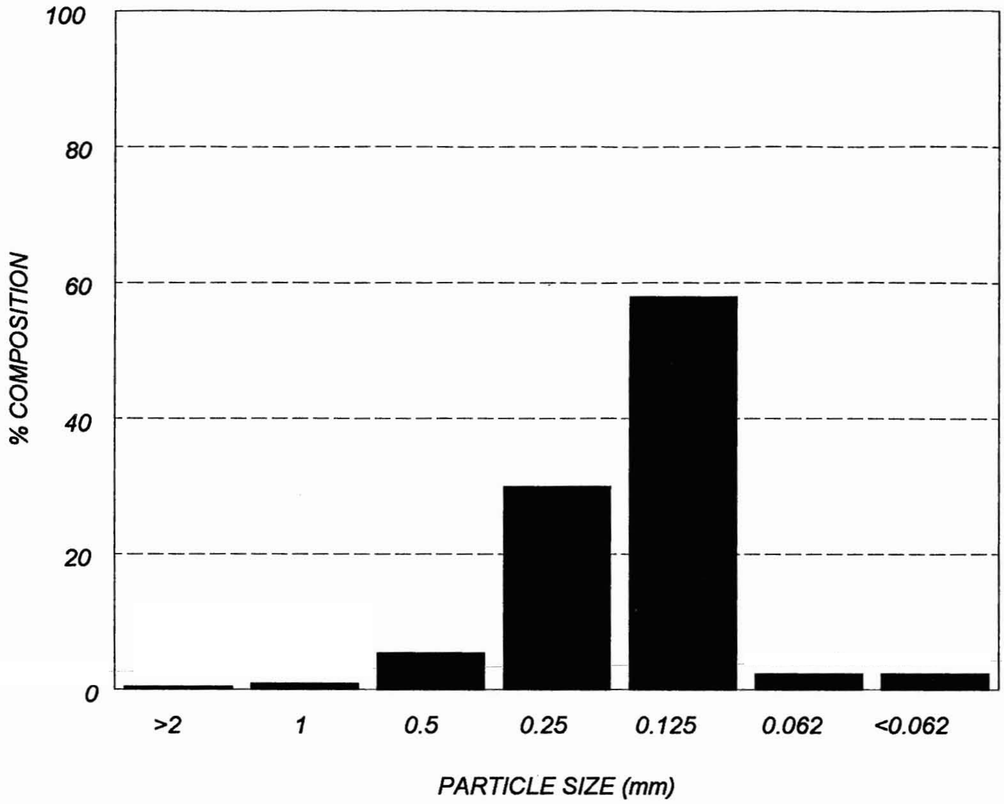

FIGURE 6. Sediment grain size distribution of the "sand" area.

ciated with a relatively immobile substrate (rubble).

Because rubble supports a more diverse community with greater macrofaunal densities and biomass than sand areas, it is important to monitor the dynamics of this habitat. Production of rubble is facilitated by relatively uncommon, yet large wave events. By producing rubble, these wave events may play a critical role in the diversity, density, and biomass of the shallow-water benthic communities of Hawai'i. Destruction of the rubble habitat by burial could adversely impact the higher trophic levels that rely on the rubble community for food. The addition of sediments to the coastal area (e.g., beach nourishment) could result in increased burial rates of the rubble and may reduce the size of this habitat. Because changes in the amount of rubble could have far-reaching impact on the biology of Hawai'i's coastal area, the dynamics of this habitat should be studied further.

ACKNOWLEDGMENTS

We thank E. A. Laws, S. V. Smith, E. A. Kay, and D. Luther for helpful comments and valuable advice during this research project. This manuscript was greatly improved by the comments of two anonymous referees.

LITERATURE CITED

ARMY CORPS OF ENGINEERS. 1994. Coastal data information program: Annual summary—1993. Pages 10–18. La Jolla, California.

BAILEY-BROCK, J. H. 1979. Sediment trapping by the chaetopterid polychaetes on a Hawaiian fringing reef. J. Mar. Res. 37(4): 643–656.

BROCK, R. E., and J. H. BROCK. 1977. A method for quantitatively assessing the infaunal community in coral rock. Limnol. Oceanogr. 22(5): 948–951.

BROCK, R. E., and S. V. SMITH. 1983. Response of coral reef cryptofaunal communities to food and space. Coral Reefs 1: 179–183.

BUCHANAN, J. B. 1984. Sediment analysis. Pages 41–65 *in* N. A. Holme and A. D. McIntyre, eds. Methods of the study of marine benthos. Blackwell Scientific Publ., Oxford.

DENNY, M. W. 1988. Biology and the mechanics of the wave-swept environment. Princeton University Press, Princeton, New Jersey.

GALLAGHER, E. D., P. A. JUMARS, and D. D. TRUEBLOOD. 1983. Facilitation of soft-bottom benthic succession by tube builders. Ecology 64(5): 1200–1216.

HARTNOLL, R. G. 1983. Substratum. Pages 97–125 *in* Earll R. Erwin and D. G. Erwin, eds. Sublittoral ecology: The ecology of the shallow sublittoral benthos. Clarendon Press, Oxford.

HISCOCK, K. 1983. Water movement. Pages 58–96 *in* Earll R. Erwin and D. G. Erwin, eds. Sublittoral ecology: The ecology of the shallow sublittoral benthos. Clarendon Press, Oxford.

HOGUE, E. W., and C. B. MILLER. 1981. Effects of sediment microtopography on small-scale spatial distributions of meiobenthic nematodes. J. Exp. Mar. Biol. Ecol. 53: 181–191.

JONES, A. R. 1984. Sedimentary relationships and community structure of benthic crustacean assemblages of reef-associated sediments at Lizard Island, Great Barrier Reef. Coral Reefs 3: 101–111.

LAMBSHEAD, P. J. D., H. M. PLATT, and K. M. SHAW. 1983. The detection of differences among assemblages of marine benthic species based on an assessment of dominance and diversity. Nat. Hist. 17: 859–874.

LAWS, E. A., J. HIRAOKA, M. MURA, B. PUNU, T. RUST, S. VINK, and C. YAMAMURA. 1994. Impact of land runoff on water quality in an Hawaiian estuary. Mar. Environ. Res. 38: 225–241.

MCCARTHY, S. A. 1996. Patterns of spatial and temporal variability in Hawaiian soft bottom benthos. Ph.D. dissertation, University of Hawai'i at Mānoa, Honolulu.

MYERS, A. A. 1985. Shallow water, coral reef and mangrove amphipoda (Gammaridea) of Fiji. Rec. Aust. Mus. 5: 1–143.

SEBENS, K. P. 1991. Habitat structure and community dynamics in marine benthic systems. Pages 211–234 *in* S. Bell, E. D. McCoy, and H. R. Mushinsky, eds. Habitat structure: The physical arrangements of objects in space. Chapman and Hall, New York.

SUN, B., and J. W. FLEEGER. 1994. Field experiments on the colonization of meiofauna into sediment depressions. Mar. Ecol. Prog. Ser. 110: 167–175.

THISTLE, D. 1981. Natural physical disturbances and communities of marine soft bottoms. Mar. Ecol. Prog. Ser. 6: 223–228.

VAN BLARICOM, G. R. 1982. Experimental analysis of structural regulation in a marine sand community exposed to oceanic swell. Ecol. Monogr. 52(3): 283–305.

WARWICK, R. M. 1986. A new method for detecting pollution effects on marine macrobenthic communities. Mar. Biol. (Berl.) 92: 557–562.

WARWICK, R. M., T. H. PEARSON, and Ruswahyuni. 1987. Detection of pollution effects on marine macrobenthos: Further evaluation of the species abundance/biomass method. Mar. Biol. (Berl.) 95: 193–200.

WOODIN, S. A. 1978. Refuges, disturbance, and community structure: A marine soft bottom example. Ecology 59(2): 274–284.

YAP, H. T., A. R. F. MONTEBON, and R. M. DIZON. 1994. Energy flow and seasonality in a tropical coral reef flat. Mar. Ecol. Prog. Ser. 103: 35–43.